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Coalitionally stable pricing schemes for inter-domain forwarding

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ABSTRACT

In this work, we model and analyze the problem of stable and efficient pricing for inter-domain traffic routing in the future Internet. We consider a general network topology with multiple sources and sinks of traffic, organized into separate domains managed by Internet Service Providers (ISPs) solely interested in maximizing their own profit. In this framework, we prove that there exists a pricing scheme that attains network-wide efficiency and is yet coalitionally stable, where the coalitions correspond to the ISPs that are acting in self-interest. This implies that this pricing scheme not only maximizes the overall utility of the resulting traffic flows, but is also such that ISPs cannot expect to improve their profit through deviation from it, even if multiple ISPs deviate at the same time. Through simulations on scale-free preferential attachment network topology models as well as actual inter-domain topologies obtained from the CAIDA database, we evaluate the convergence of best-response based simple price updates, and show that they quickly attain near-optimal network utility in these network topologies.

1. Introduction

1.1. Background and motivation

Current inter-domain traffic routing and pricing practices are typically driven by simple heuristic rules and policies, and do not in general optimize the overall use of Internet resources. Inter-domain routing follows the Border Gateway Protocol (BGP) standard [41] that only attempts to minimize the number of ISP hops on the path of a flow, in addition to following local policy considerations and certain heuristic rules. Traffic exchange contracts between ISPs are mostly negotiated manually and span months, even years. Even at these long timescales, these contracts are often simplistic, with no detailed quality metrics, and usually specifying a minimum base traffic volume for charging. Charging is typically done based on the total traffic offered by the customer ISP, irrespective of their destination; this is also referred to as 'point-to-anywhere pricing' [43]. It has been argued correctly that point-to-point or destination-based pricing can result in better efficiency of network resource usage [48]. Moreover, recent measurements also show fast-changing patterns for inter-domain traffic [30]; inter-domain service pricing and traffic engineering solutions need to be flexible enough to adapt to such dynamically changing traffic patterns, as well as variations in customer requirements and their willingness to pay.

High-efficiency inter-domain traffic engineering involves many challenges ranging from technical capabilities to economics and policy [16]. One of the difficulties is that it requires involvement of (agreement by) multiple Internet Service Providers (ISPs) that are naturally interested in maximizing their own profits, and their individual

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objectives are often in conflict with each other. While multi-ownership is in general essential for competition, efficiency, and growth of a system, the multi-provider structure of the Internet has been a hindrance toward attaining efficiency in routing beyond individual ISP or Autonomous Systems (AS) boundaries. These facts also imply that an inter-domain traffic engineering solution will only be adopted easily if it allows individual ISP business goals and policies to be respected, and is economically profitable/justifiable to each ISP. Another challenge in this context is the counter-productive effects of intra-domain and inter-domain traffic engineering policies if they are not designed with careful consideration of their interaction with each other [2,5,24].

Economically driven inter-domain traffic engineering is a challenging task, and in this work we undertake some initial steps toward studying this complex yet important issue. We provide and analyze a game-theoretic model of price-setting by ISPs that are solely interested in maximizing their individual profits, taking into account the changes to the traffic pattern resulting from this price change. We study the question whether a "good" equilibrium exists, i.e., whether there exists a price-setting solution from which profit-maximizing ISPs would not deviate from (out of self-interest), and yet results in a traffic flow that maximizes the overall network utility (social welfare).

1.2. Focus of this work

The pricing and forwarding questions for inter-domain traffic are intertwined: the "price of forwarding" as chosen by an ISP will naturally impact the traffic it receives, as it will determine how much traffic its neighboring ISPs will offer. Similarly, traffic routing by an ISP from the ingress to the egress nodes through its internal network will depend on the prices offered by its neighboring nodes, since each ISP would naturally like to send flow to the destination at minimum cost. The question we study in this paper involves finding the "right" price that ISPs should charge for traffic forwarding services within the framework of destination-based, next-hop routing, which is the current Internet practice. Note that an ISP obtains payments from its upstream neighbors for accepting their traffic for forwarding, and must in turn pay its downstream neighbors for receiving its traffic (i.e., the traffic it has accepted to forward, plus the traffic that originates within its own network).

We assume that ISPs are interested in maximizing their individual profits, defined as the revenue (or utility) an ISP earns by accepting its neighbors' traffic as well as that of its own subscribers (end-users), minus the cost incurred for sending traffic to its neighbors. In this framework, the question we consider in this paper is how inter-domain traffic forwarding services should be priced so that it is *stable* and *efficient*. Posed another way, we address the question of whether efficient inter-domain traffic engineering can be realized within a framework where ISPs compete with each other for traffic and revenue. More specifically, this comprises of studying the two following issues: (i) The existence of equilibrium prices, from which ISPs (with the ability to anticipate how the traffic would vary in response to price changes) would not have any incentive to deviate; (ii) The efficiency of this pricing equilibrium, in terms of maximizing the overall network utility (generalized throughput) defined solely in terms of the traffic flows.

Since we pose our question as a complete information game, our model implicitly assumes that ISPs can correctly anticipate (or estimate) the effect of their price changes on the traffic patterns. Computing such an equilibrium would in general require global knowledge, and is therefore infeasible in practice. Therefore we also explore the convergence of an incremental best-response based price update policy that is motivated by price update/discovery mechanism used in a typical market-place. This incremental price update strategy can be implemented without knowledge of the network, the impact of the price change being inferred simply by observing the changed behavior of the flows reacting to the price change (the price update is assumed to occur in a relatively slow timescale for this to happen).

1.3. Contribution and significance

We provide a game-theoretic model of price-setting by ISPs, where each ISP is solely interested in maximizing its profits, while anticipating (or estimating) the changes to the overall traffic pattern that will result from changes to its pricing scheme. We establish the existence and efficiency of a *coalitional equilibrium* for this game, where each coalition corresponds to an ISP network. In our model, an ISP is represented as a *cloud* – a subnetwork of nodes (routers) and edges (links) connected in an arbitrary topology, or even a collection of (possibly disjoint) subnetworks. This general ISP model is well representative of the administrative structure in the current Internet where an ISP can control multiple Autonomous Systems (ASes) [53], and is much more general than models which assume that each ISP consists only of a single node in the network (see Section 2). Our view of ISPs as coalitions aligns well with the fact that an ISP will jointly optimize the prices it quotes at all its ingress points, along with the traffic forwarding paths inside its network.

The concept of stability (coalitional equilibrium) considered by us is substantially strong: It is resilient to (i) ISPs being optimistic about the flows that may result from changing their price; (ii) any ownership (coalition) structure in the network, or equivalently, any partitioning of the network (Internet) into ISP boundaries. The notion of social optimality we consider amounts to maximizing the aggregate utility (generalized network throughput) in the entire network (Internet); and this does not need to take into account the ISP boundaries. Note that our notions of *coalitional equilibrium* and *coalitional stability* are also alternatively known in the literature as *strong Nash equilibrium* and *strong stability* (of Nash equilibria), respectively.

Despite our strong stability concept, we show that socially optimal flows are stabilizable, i.e., we show how to compute prices which together with a socially optimal flow lead to a coalitional equilibrium. In other words, we show that the price-of-stability (PoS) is unity: there are stable solutions which are as good as the social optimum, and so we do not need to sacrifice any social welfare in